ARMY RESEARCH LABORATORY

Experiments in a 120-mm Ram Accelerator at Elevated Pressures

D. L. Kruczynski
A. W. Horst
F. Liberatore

ARL-TR-1236

November 1996

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1996

3. REPORT TYPE AND DATES COVERED
Final, March 1993 - June 1993

4. TITLE AND SUBTITLE
Experiments in a 120-mm Ram Accelerator at Elevated Pressures

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
D. Kruczynski, A. Horst, and F. Liberatore

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1236

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Ram acceleration is an emerging propulsion technology in which a projectile similar in shape to the centerbody of a ramjet aircraft engine is injected into a tube filled with a combustible gaseous mixture. As the projectile moves into the tube under supersonic conditions, shocks occur on and around the projectile. If the gases ignite, the combustion can be self-sustaining, generating a localized high-pressure region that travels with the projectile producing acceleration. Velocities of more than 2.6 km/s have been experimentally demonstrated, while theory predicts velocities above 7 km/s are obtainable.

The U.S. Army Research Laboratory (ARL) is studying the physics of the ram acceleration process through an integrated experimental and computational fluid dynamics effort. ARL operates the world's largest ram accelerator at 120-mm bore size.

Initial experimental results at this facility are presented. In addition, data from experiments at gaseous fuel pressures up to 102 atm are presented. Impact of "high pressure" operation on facility design and application are considered. Finally, future plans are summarized.

14. SUBJECT TERMS
ram accelerator, hypervelocity gun, subsonic combustion, high pressure combustion

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENTS

The author acknowledges Dr. Thomas Minor for his continued support; Mr. Michael Nusca for critical insights provided by his companion CFD research; Messrs. Robert Hall, James Bowen, John Hewitt, James Tuerk, Dennis Meier, Joseph Colburn, Arthur Koszoru, and Carl Ruth for continued experimental support; Mr. Maher Kiwan for engineering, analytical, and experimental support; and Dr. Carl Knowlen and Professor Adam Bruckner for numerous technical insights.

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

LIST OF TABLES

INTENTIONALLY LEFT BLANK.

1. BACKGROUND

1.1 The Process. Ram acceleration is an emerging propulsion technology capable of accelerating large masses to hypervelocities. Ram acceleration is produced when a suitably shaped projectile is injected at supersonic velocity into a tube prefilled with a combustible gas mixture. As the projectile enters the tube, gas shocks are produced. These shocks heat, slow, and pressurize the gas, causing combustion to occur around and behind the projectile. This combustion process travels with the projectile producing continuous acceleration over the length of the accelerator tube. The in-tube ram accelerator concept, developed by the University of Washington's (UW) Aerospace and Energetics Research Program, is an offshoot of ramjet engine technology (Hertzberg, Bruckner, and Bogdanoff 1988; Knowlen, Bruckner, and Hertzberg 1992; Hinkey, Burnham, and Bruckner 1992). The process is shown in Figure 1.

1.2 The Army Research Laboratory and Ram Acceleration. In 1991 the U.S. Army Research Laboratory (ARL) embarked on a program entitled Hybrid Inbore Ram Acceleration (HIRAM) (Kruczynski 1991a, 1991b). The term "hybrid" naturally rises from the fact that, currently, ram accelerators require a prelauncher to bring the ram projectile up to take over velocity for the ram process. The HIRAM program was designed to develop a launcher for economically and routinely accelerating 7-kg masses to velocities approaching 3 km/s for hypervelocity launch and terminal effects studies. The HIRAM system was designed with significant expansion capability to study other applications such as terminal missile defense and ground-launch-to-space.

The ARL test facility consists of accelerator tubes made from retired 120-mm M256 tank guns, machined and mated. Transition from the solid propellant launcher to the accelerator is made through a transition/vent section. This section serves the dual purpose of decoupling the conventional launch gun recoil from the accelerator (sliding interface) and venting the backpressure from the conventional charge combustion. The HIRAM facility was initially designed to accommodate five 4.7-m-long accelerator tubes for a total combined length of 23.5 m. Expansion to 60 m is possible. The initial experiments reported here were performed using a single 4.7-m accelerator section. Gases are supplied from a bottle farm and diaphragm compressor capable of supplying five different gases at pressures up to 341 atm. A large vacuum pump installed near the accelerator is capable of evacuating any part of the launch/vent/accelerator assembly as desired.

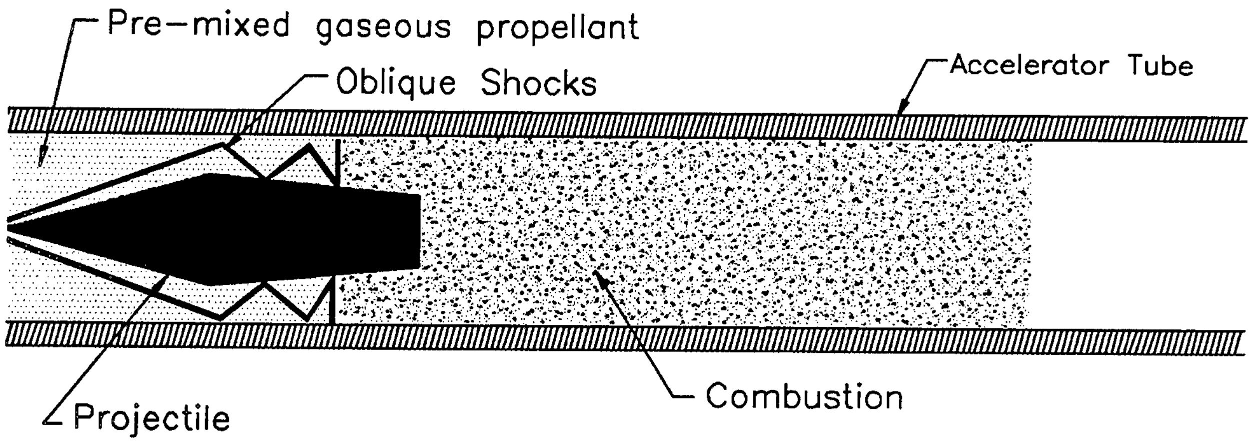

Figure 1. Schematic of ram acceleration process.

Instrumentation within the accelerator tube includes wall-mounted quartz pressure transducers and photodiode gages. High-speed movie and still-frame (smear) cameras are employed at various locations around the accelerator. Doppler radar and other devices are used to measure projectile exit and inbore velocity. Gas samples are taken just prior to firing for later analysis. The projectile is made of high-strength aluminum alloy and weighs 4.29 kg. Kruczynski (1991b) provides additional details about the HIRAM facility.

1.3 Scaling Tests. Following 19 months of extensive experimental and computational fluid dynamics (CFD) efforts, the HIRAM program was successful in demonstrating ram acceleration in the largest ram accelerator in the world, at 120-mm bore diameter (Nusca 1991a, 1991b, 1992; Kruczynski and Nusca 1992; Kruczynski 1992). The results from these initial firings in a 4.7-m-long accelerator tube are shown in Table 1. These tests represented the second time the technology has been successfully scaled (see Giraud et al. [1992] and Giraud, Legendre, and Simon [1992] for details of the Institute of Saint Louis [ISL] 90-mm cal. work).

2. "HIGH-PRESSURE" FIRINGS - THE RATIONALE

2.1 Accelerator Fill vs. Combustion Pressure. In firings conducted at the UW ram facility, a relatively linear relationship between the accelerator fuel/oxidizer/diluent pressure and the peak combustion pressures achieved during operation was established. In general, combustion pressures were about 15 to

Table 1. Scaling Tests in 120-mm Ram Accelerator

Test No.	Entrance Velocity (m/s)	Exit Velocity (m/s)	Velocity Gain (m/s)	Average Acceleration G's
15	1,175	1,419	244	7,800
16	1,178	Injection Test		
17	1,190	862	Unstart	
18	1,180	1,440	260	8,400
19	1,182	1,410	228	6,200

20 times the level of the fuel/oxidizer/diluent pressure (Kruczynski 1992). This relationship had been verified at fuel/oxidizer/diluent pressures up to 50 atm in experiments at the UW.

In the remainder of this report the term fuel/oxidizer/diluent will be referred to simply as fuel.

The ARL ram acceleration facility is unique among current facilities in its ability to operate at much higher fuel pressure. The current design of the HIRAM facility allows for operation at fuel pressures exceeding 100 atm. The series of "high-pressure" firings reported herein was designed to exploit this ability and develop data for fill vs. combustion pressure at much higher pressures than previously obtained.

2.2 Performance. The second reason for conducting these "high-pressure" firings is based on HIRAM performance requirements. With projectile properties such as throat diameter, cone angle, afterbody angle, and material identical, the projectile mass increases much more quickly than the projectile area available for the propulsion pressures to act upon as systems are scaled up. Table 2 compares typical physical data and empirical performance estimates to obtain 10,000 G's of constant acceleration in the three current facilities.

It is apparent from Table 2 that as accelerator scale increases, either operating pressures or accelerator lengths must be increased to obtain similar velocity gains. Indeed the ability of the ram accelerator to trade off length with operating pressures (acceleration) and vice versa is one of the technologies' greatest attractions.

Table 2. Typical Properties of Current Ram Accelerators

Property	System Caliber (mm)		
	38	90	120
Projectile mass (kg)	.09	1.23	4.29
Throat Area (m^2)	0.00066	0.00385	0.00665
Mass/Area (kg/m^2)	136	320	645
Combustion Pressure for 10 kG's Constant Acceleration (Atm)	132	309	625

As previously mentioned, in the HIRAM system, it was deemed desirable to operate at higher pressures than previously attempted to shorten the required accelerator length for the comparatively heavy projectile.

2.3 Chemical Kinetics. The final reason for these higher pressure firings was the possibility of learning more about the chemical kinetics of high pressure methane combustion for use in CFD codes. It was felt that increases in peak and average combustion pressures at several elevated pressures might be empirically related to combustion rate coefficients. These data might be used to fine-tune inhouse CFD codes until more robust data were available. This work is still in progress and will be reported in the future.

3. "HIGH-PRESSURE" FIRINGS

As shown previously in Table 1, the first HIRAM firings were conducted with fuel pressures of 50 atm and a fuel mixture (on a molar basis) of $2O_2 + 10N_2 + 3CH_4$. This fuel mixture (and projectile entrance Mach number) was kept constant in the high-pressure series. At a fuel-to-combustion pressure ratio of 20, this would produce combustion pressures near the HIRAM's safe operating limit of 2,000 atm at fill pressures of 100 atm.

Figures 2–5 show typical pressure vs. time curves measured at the accelerator wall as the projectile and combustion pass a point approximately midway into the 4.7-m-long accelerator section. Figure 2 is

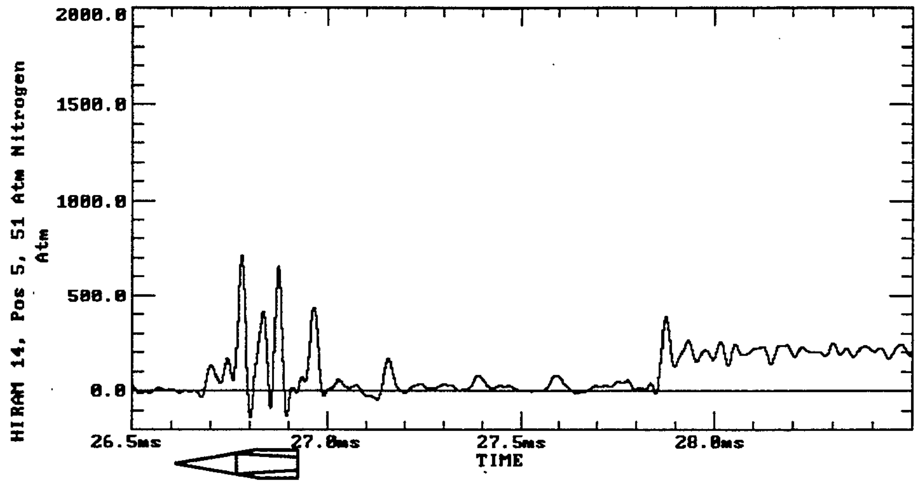

Figure 2. HIRAM shot into 51 atm nitrogen. Projectile scaled to local velocity.

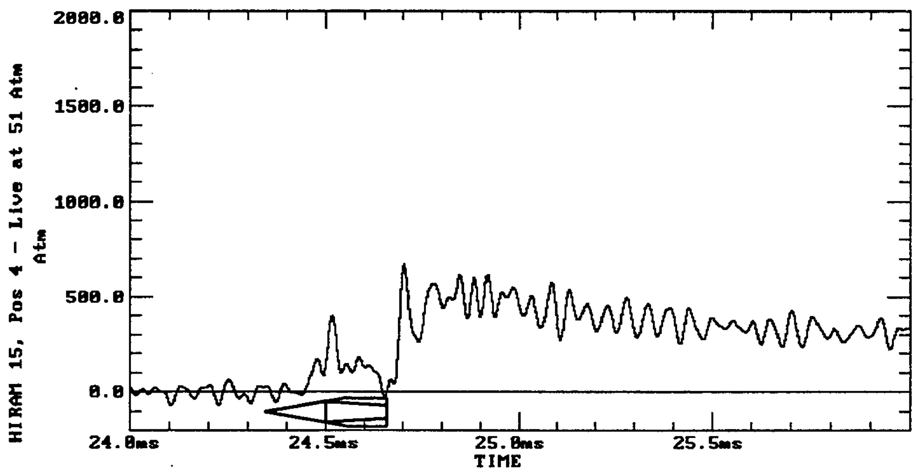

Figure 3. HIRAM shot into 51 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Projectile scaled to local velocity.

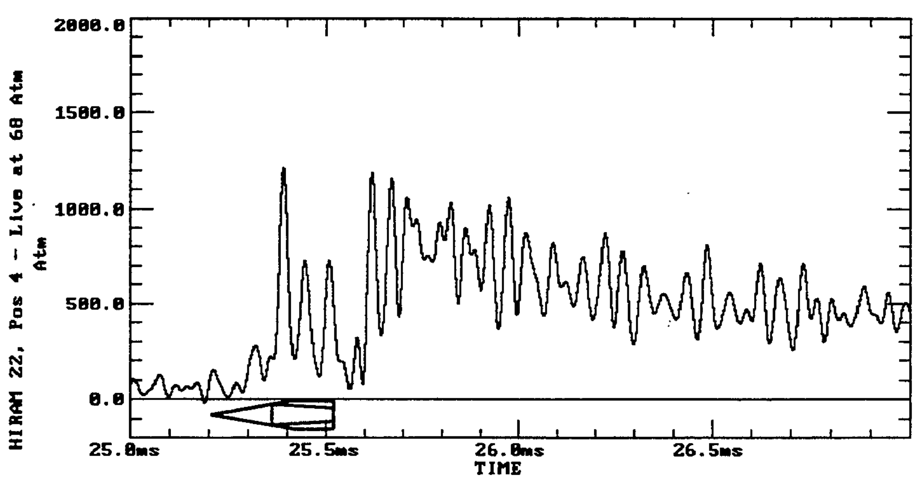

Figure 4. HIRAM shot into 69 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Projectile scaled to local velocity.

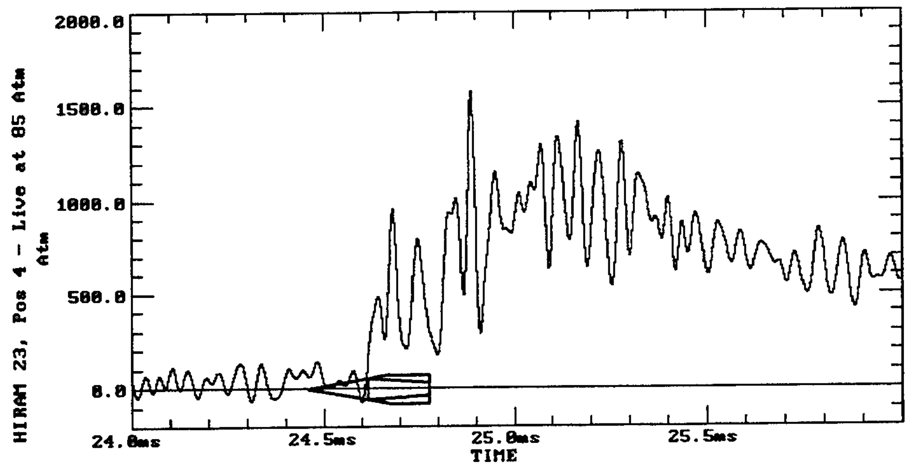

Figure 5. HIRAM shot into 85 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Projectile scaled to local velocity.

for an inert firing with the accelerator charged to 51 atm of nitrogen. Figures 3–5 show data from live gas shots conducted with fuel pressures of 51, 69, and 85 atm. Note that Figures 3–5 (plotted with the same maximum ordinate) show a steady progression of combustion pressure levels as fuel charge pressures are raised. High-speed movies of the projectile and combustion exiting the accelerator reveal that as the combustion pressures rise, the intensity of combustion increases (as revealed by increased light emission).

Figure 6 shows the relationships between the fuel fill pressure and the resultant peak combustion pressure. Note, that for this fuel mixture and entrance Mach number, the ratios of peak combustion pressure-to-fuel charge pressures are 13, 18, and 19, respectively. Although there seems to be a slight increase in this ratio as the fuel pressure is increased, these values are consistent with those reported earlier by UW at lower pressures and higher heat release values (Kruczynski 1992). Note that the relatively low pressure ratio value for the 51-atm shot may indicate that this fuel mixture is at the low end of allowable heat release values to sustain combustion.

The velocity gain vs. fuel and combustion pressure relationship is not completely clear due to several effects. For instance, in the shot with 69 atm of fuel pressure, a small steel nosetip used at the front of the aluminum projectile to assist in piercing the diaphragms came off at some point in the accelerator. Although the projectile did not unstart (combustion moves forward of projectile), there was considerable combustion activity around the nose area at projectile exit. This combustion along with additional drag from the large, flat, exposed frontal area combined to reduce the velocity gain in this shot to 65 m/s. For

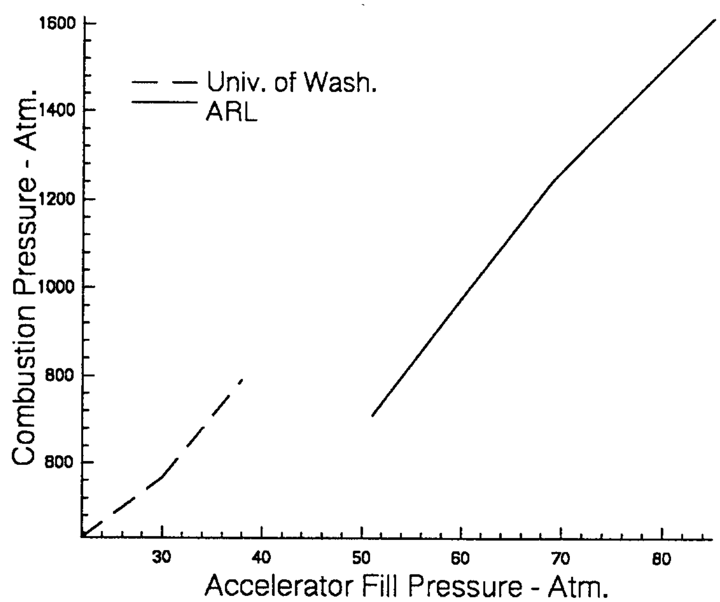

Figure 6. Plot of peak combustion pressure as a function of fuel pressure.

reference, the shot with 51-atm fuel pressure achieved a 249-m/s velocity gain. The shot at 85 atm achieved a 297-m/s gain. Although this is not quite the velocity gain expected for the drive pressure produced, some of the difference is probably accounted for by higher drag at the increased fuel pressures and some combustion activity ahead of the throat due to faster fuel kinetics at the higher pressures. Also, variability in fuel composition could reduce the velocity gain.

In short, there are too few data points at this time to draw conclusions relative to velocity gain at these higher pressures although a positive trend is clearly seen in the 85 atm shot. A shot conducted at a fuel pressure of 102 atm resulted in an unstart shortly after entry into the ram accelerator and is detailed in the next section.

4. "HIGH-PRESSURE" UNSTART

A shot attempted with the fuel pressure at 102 atm resulted in an unstart after a meter of projectile travel in the accelerator. Figures 7–10 show the pressure curves at various positions in the accelerator during this shot. In Figure 7, the projectile has just entered the accelerator and the initial pressure plot shows a started diffuser much like previous successful shots. The next position (1.15 m into the accelerator), shown in Figure 8, reveals an incipient unstart condition. In Figures 9 and 10, the "combustion wave" is seen to overtake and outrun the projectile.

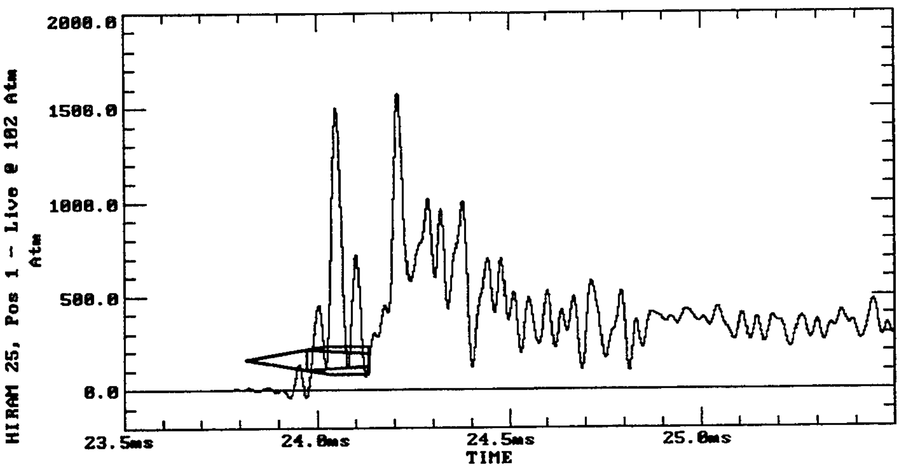

Figure 7. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Diffuser is starting.

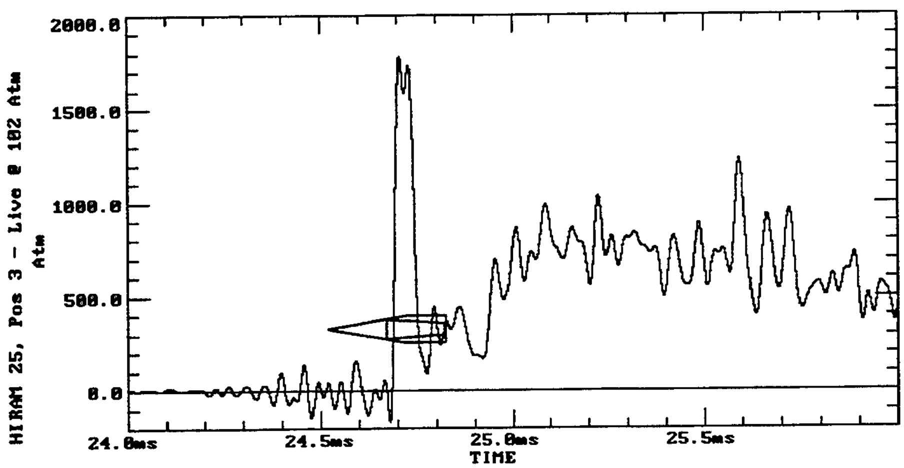

Figure 8. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Incipient unstart condition.

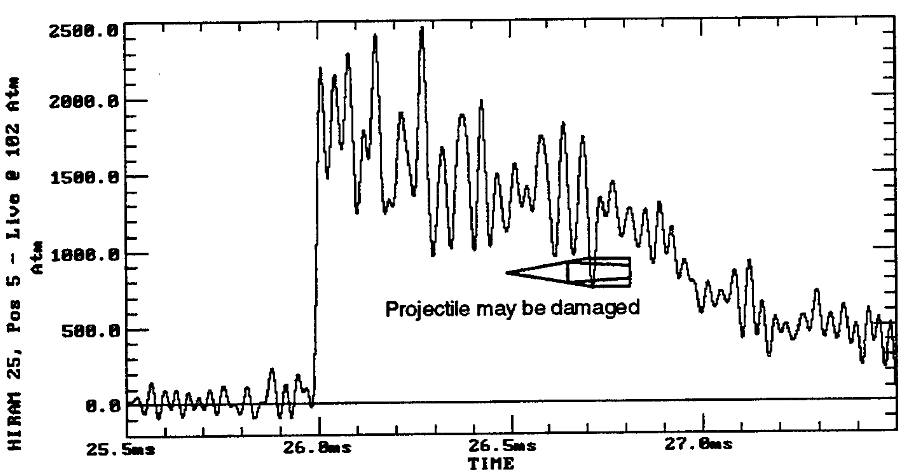

Figure 9. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Combustion wave is masking projectile location.

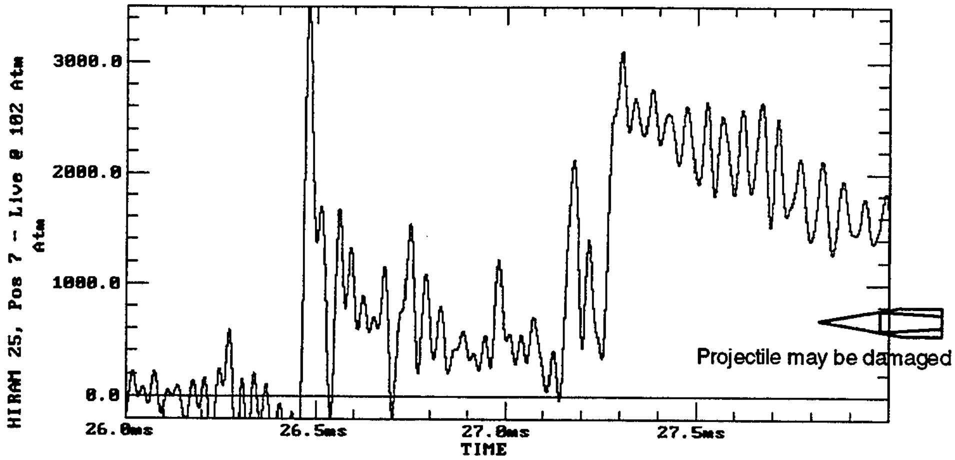

Figure 10. HIRAM shot into 102 atm fuel ($2O_2 + 10N_2 + 3CH_4$). Detonation wave has outrun projectile.

High-speed movies of this shot clearly show two zones of combustion at the accelerator exit. The first is a narrow combustion zone that breaks the end diaphragm. This is followed by a larger "dark zone" that exists for about a millisecond before a second and larger (and more violent) combustion occurs. This photographic evidence matches the pressure forms seen in Figure 10. Additional insight into these high-pressure phenomena is contained in Nusca (1993).

The exact cause for this, and many unstarts, is not certain. There are several possibilities that may, or more likely, may not be independent. The most obvious is that for this fuel mixture, the pressure increase causes chemical reactions to occur so rapidly, the projectile cannot "outrun" the intense combustion that occurs at the projectile-obturator interface. However, there was little evidence that this would occur from the earlier high-pressure firings up to 85 atm.

A second suspected unstart mechanism could be nonuniform mixing of the fuel gases that would cause local pockets of higher energy gases (Knowlen 1993). The HIRAM system is the only system that currently uses the partial pressure method to obtain proper gas ratios. Although samples taken at time of firing reveal that the mixtures are generally within the range desired, there is considerable variation from test to test. This variability is of some concern and is under further study. Of nine live-fuel shots performed to date in the HIRAM system, two have resulted in unexplained unstarts.

Finally, the structural integrity of the projectile may, in some cases, be suspect. In the two unstarts just noted, the projectile was broken into several pieces as detailed by exterior photography. It is more

likely, however, that the unstart is the cause of projectile failure as high-pressure combustion drives through the throat and large deceleration loads are applied. This too is undergoing additional study.

5. EFFECTS OF UNSTARTS ON HARDWARE

During an unstart, the pressure may rise to levels 50 times the fuel pressure. This is contrasted with the 20 fold rise typically induced during normal operation. Designing a system with a pressure safety margin for unstarts may significantly increase tube length for a given velocity gain. For instance, an accelerator tube with a yield stress of 7,000 atm to be operated with a safety factor of 2 would require that operation be limited to fuel pressures no greater than 70 atm, 7,000 over 2×50. For applications where shorter tubes are of more interest than low acceleration levels, this constraint can be daunting.

During the high-pressure tests previously described, a conscious decision was made to operate with fuel pressures sufficient to cause combustion pressures in excess of accelerator and projectile yield strength in the event of an unstart. It was felt by the investigators that sufficient evidence existed that such events might either be artifacts of gage response, or of such short duration that the accelerator tube would not respond to the narrow, short-duration pressure spikes. Gage malfunctions cannot be ruled out as the cause for these spikes, however, considerable data exists at UW that supports the conclusion that these are indeed real events (Knowlen 1993).

During several recent unstarts in the HIRAM system, the design yield strength of the accelerator tube has been exceeded by 10% or better based on short-duration pressure spikes measured at the accelerator wall. These pressure spikes vary in duration from approximately 0.05 to 0.1 ms. Subsequent inspections of the tube inside with a borescope (visual inspection) and outside with magnetic particle and eddy current techniques revealed no wear or damage of any type. The long-term effects of overloading the tube in this manner on fatigue life are not clear.

The authors ARE NOT recommending that these short-duration pressure spikes be ignored. However, for protected test ranges where a tube failure could be safely contained, the risk involved in an occasional moderate pressure unstart approaching or slightly exceeding the yield stress of the tube material may be an acceptable calculated risk. As ram accelerator phenomenology is better understood, and the technology is focused on well-known and repeatable conditions (such as would be encountered in a fielded weapon),

it should be possible to design systems in which unstarts would be eliminated or reduced to an acceptable level.

6. SUMMARY AND CONCLUSIONS

It has been shown that:

- Ram acceleration technology can be scaled relatively easily to larger bore sizes capable of carrying useful payloads.

- Ram accelerators can be safely operated at fuel pressures over 100 atm and combustion pressures approaching 1,700 atm. Safe operation at even higher pressures is thus quite possible. The ability to operate a ram accelerator at "high pressures" is of considerable value for applications more concerned with short launchers than high acceleration loads.

- High-pressure unstarts, while a cause for continued concern, do not necessarily limit the upper operating range of ram accelerators for some applications.

7. FUTURE

Future work in the HIRAM facility will key on flow visualization and other diagnostics, and increased performance (optimization) techniques.

INTENTIONALLY LEFT BLANK.

8. REFERENCES

Giraud, M., J. F. Legendre, G. Simon, and L. Catoire. "RAM Accelerator in 90-mm Caliber, First Results Concerning the Scale Effect In the Thermally Choked Propulsion Mode." Proceedings of the 13th International Symposium on Ballistics, Stockholm, Sweden, 1–3 June 1992.

Giraud, M., J. Legendre, and G. Simon. "RAM Accelerator Studies in 90-mm Caliber." 43rd Meeting of the Aeroballistic Range Association, Columbus, OH, 28 September–2 October 1992.

Hertzberg, A., A. Bruckner, and D. Bogdanoff. "Ram Accelerator: A New Chemical Method for Accelerating Projectiles to Ultrahigh Velocities." AIAA Journal, vol. 26, pp. 195–203, 1988.

Hinkey, J., E. Burnham, and A. Bruckner. "High Spatial Resolution Measurements in a Single Stage Ram Accelerator." 29th JANNAF Combustion Subcommittee Meeting, Hampton, VA, 19–23 October 1992.

Knowlen, C., A. Bruckner, and A. Hertzberg. "Internal Ballistics of the Ram Accelerator." Proceedings of the 13th International Symposium on Ballistics, Stockholm, Sweden, 1–3 June 1992.

Knowlen, C. Private communication. University of Washington, June 1993.

Kruczynski, D. "Analysis of Ram Acceleration for High Velocity Applications." AIAA Paper 91-2488, AIAA/SAE/ASME/ASEE 27th Joint Propulsion Conference, Sacramento, CA, 24–26 June 1991a.

Kruczynski, D. "Requirements, Design, Construction, and Testing of a 120-mm Inbore Ram Accelerator." 28th JANNAF Combustion Meeting, CPIA publication 573, vol. 1, October 1991b.

Kruczynski, D. "Experimental Demonstration of a 120-mm Ram Accelerator." 29th JANNAF Combustion Subcommittee Meeting, Hampton, VA, 19–22 October 1992.

Kruczynski, D., and M. Nusca. "Experimental and Computational Investigation of Scaling Phenomena in a Large Caliber Ram Accelerator." AIAA paper 92-3245, AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, TN, 6–8 July 1992.

Nusca, M. "Numerical Simulation of Reacting Flow in a Thermally Choked Ram Accelerator Projectile Launch System." AIAA paper 91-2490, AIAA/SAE/ASME/ASEE 27th Joint Propulsion Conference, Sacramento, CA, 24–26 June 1991a.

Nusca, M. "Navier-Stokes Simulation of Fluid Dynamic and Combustion Phenomena in the RAM Accelerator." 28th JANNAF Combustion Meeting, CPIA publication 573, vol. 1, October 1991b.

Nusca, M. "Navier-Stokes Simulation of Transient Fluid Dynamics and Initiation of Combustion in the Ram Accelerator." 29th JANNAF Combustion Subcommittee Meeting, Hampton, VA, 19–22 October 1992.

Nusca, M. "Numerical Simulation of Fluid Dynamics with Finite-Rate and Equilibrium Combustion Kinetics for the 120-mm Ram Accelerator." AIAA-93-2182, Proceedings of the 29th AIAA Joint Propulsion Conference, Monterey, CA, 28–30 June 1993.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFO CTR ATTN DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL CS AL TP 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL CS AL TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	ABERDEEN PROVING GROUND
2	DIR USARL ATTN AMSRL CI LP (305)

NO. OF COPIES	ORGANIZATION
2	HQDA ATTN SARD TT DR F MILTON MR J APPEL WASHINGTON DC 20310-0103
1	HEADQUARTERS USA MATERIAL CMD ATTN AMCICP AD M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	USA BALLISTIC MIS DEFNS SYS CMD ADV TECH CTR PO BOX 1500 HUNTSVILLE AL 35807-3801
2	COMMANDER USA ARDEC ATTN SMCAR CCH V C MANDALA E FENNELL PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR AEE J LANNON PICATINNY ARSENAL NJ 07806-5000
7	COMMANDER USA ARDEC ATTN SMCAR AEE B D DOWNS S EINSTEIN S WESTLEY S BERNSTEIN J RUTKOWSKI B BRODMAN P HUI PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR AEE WW M MEZGER PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER USA ARDEC ATTN SMCAR FSA F LTC R RIDDLE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR FS T GORA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR FS DH J FENECK PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER USA ARDEC ATTN SMCAR FSN N K CHUNG A BAHIA R LEE PICATINNY ARSENAL NJ 07806-5000
2	DIRECTOR BENET WEAPONS LABORATORIES ATTN SMCAR CCB RA G OHARA G PFLEGL WATERVLIET NY 12189-4050
1	DIRECTOR BENET WEAPONS LABORATORIES ATTN SMCAR CCB S S HEISER WATERVLIET NY 12189-4050
2	COMMANDER USA RSRCH OFC ATTN TECH LIB D MANN PO BOX 12211 RESEARCH TRIANGLE PARK NC 227709-2211

NO. OF COPIES	ORGANIZATION
1	COMMANDER USA CECOM ATTN ASQNC ELC IS L R MYER CTR R&D TECH LIB FORT MONMOUTH NJ 07703-5301
1	COMMANDER USA BELVOIR R&D CTR ATTN STRBE WC FORT BELVOIR VA 22060-5006
1	COMMANDER USA FSTC ATTN AMXST MC 3 220 SEVENTH ST NE CHARLOTTESVILLE VA 22901-5396
1	USA RSRCH OFC (UK) PSC 802 BOX 15 DR ROY E REICHENBACH APO AE 09499-1500
2	COMMANDER NAVAL SEA SYS CMD ATTN SEA 62R SEA 64 WASHINGTON DC 20362-5101
1	COMMANDER NAVAL AIR SYS CMD ATTN AIR 954 TECH LIB WASHINGTON DC 20360
1	COMMANDER NAVAL RSRCH LAB ATTN TECH LIB WASHINGTON DC 20375-5000
4	COMMANDER NAVAL RSRCH LAB ATTN CODE 6410 K KAILASANATE C LI J BORIS E ORAN WASHINGTON DC 20375-5000

NO. OF COPIES	ORGANIZATION
1	OFFICE OF NAVAL RSRCH ATTN CODE 473 R MILLER 800 N QUINCY ST ARLINGTON VA 22217-9999
1	OFFICE OF NAVAL TECHNOLOGY ATTN ONT 213 D SIEGEL 800 N QUINCY ST ARLINGTON VA 22217-5000
7	COMMANDER NSWC ATTN T SMITH K RICE S MITCHELL S PETERS J CONSAGA C GOTZMER TECH LIB INDIAN HEAD MD 20640-5000
1	COMMANDER NSWC ATTN CODE G30 GUNS & MUNITIONS DIV DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE G32 GUNS SYSTEMS DIV DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE G33 T DORAN DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE E23 TECH LIB DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE C23 G GRAFF DAHLGREN VA 22448-5000

NO. OF COPIES	ORGANIZATION
2	COMMANDER NAWC ATTN CODE 388 C PRICE T BOGGS CHINA LAKE CA 93555-6001
2	COMMANDER NAWC ATTN CODE 3895 T PARR R DERR CHINA LAKE CA 93555-6001
1	COMMANDER NAWC ATTN INFO SCI DIV CHINA LAKE CA 93555-6001
1	COMMANDING OFFICER ATTN CODE 5B331 TECH LIB NAVAL UNDERWATER SYS CTR NEWPORT RI 02840
1	AFOSR NA ATTN J TISHKOFF BOLLING AFB DC 20332-6448
1	OLAC PL TSTL ATTN D SHIPLETT EDWARDS AFB CA 93523-5000
3	OLAC PL RK ATTN J LEVINE L QUINN T EDWARDS 5 POLLUX DR EDWARDS AFB CA 93524-7048
1	WL MNAA ATTN B SIMPSON EGLIN AFB FL 32542-5434
1	WL MNME ENERGETIC MATERIALS BR 2306 PERIMETER RD STE 9 EGLIN AFB FL 32542-5910

NO. OF COPIES	ORGANIZATION
1	WL MNSH ATTN G ABATE EGLIN AFB FL 32542-5434
1	WL POPS ATTN B SEKAR BLDG 18 1950 FIFTH ST WRIGHT PATTERSON AFB OH 45433
2	NASA LANGLEY RSRCH CTR ATTN MS 408 W SCALLION D WITCOFSKI HAMPTON VA 23605
1	ELORET ATTN D BOGDANOFF MS 230 2 NASA AMES RSRCH CTR MOFFETT FIELD CA 94035-1000
1	CENTRAL INTELLIGENCE AGENCY OFC OF INFORMATION RESOURCES ROOM GA 07 HQS WASHINGTON DC 20505
1	CENTRAL INTELLIGENCE AGENCY ATTN J BACKOFEN NHB ROOM 5N01 WASHINGTON DC 20505
1	SDIO TNI ATTN L CAVENY PENTAGON WASHINGTON DC 20301-7100
1	SDIO DA ATTN E GERRY PENTAGON WASHINGTON DC 21301-7100
2	HQ DNA ATTN D LEWIS A FAHEY 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398

NO. OF COPIES	ORGANIZATION
1	DIRECTOR SANDIA NATL LABS ATTN M BAER ENERGETIC MATL & FLUID MECH DEPT 1512 PO BOX 5800 ALBUQUERQUE NM 87185
1	DIRECTOR SANDIA NATL LABS ATTN R CARLING COMBUSTION RSRCH FACILITY LIVERMORE CA 94551-0469
1	DIRECTOR SANDIA NATL LABS ATTN 8741 G BENEDETTI PO BOX 969 LIVERMORE CA 94551-0969
2	DIRECTOR LLNL ATTN L355 A BUCKINGHAM M FINGER PO BOX 808 LIVERMORE CA 94550-0622
1	DIRECTOR LOS ALAMOS SCIENTIFIC LAB ATTN T3 D BUTLER PO BOX 1663 LOS ALAMOS NM 87544
1	DIRECTOR LOS ALAMOS SCIENTIFIC LAB ATTN M DIVISION B CRAIG PO BOX 1663 LOS ALAMOS NM 87544
1	UNIV OF TEXAS AT AUSTIN INST FOR ADV TECH ATTN T KIEHNE 4030 2 W BRAKER LN AUSTIN TX 78759-5329

NO. OF COPIES	ORGANIZATION
2	CPIA JHU ATTN H HOFFMAN T CHRISTIAN 10630 LITTLE PATUXENT PKWY STE 202 COLUMBIA MD 21044-3200
1	CA INST OF TECH ATTN L STRAND MS 125 224 JET PROPULSION LAB 4800 OAK GROVE DR PASADENA CA 91109
1	CA INST OF TECH ATTN F CULICK 204 KARMAN LAB MS 301 46 1201 E CALIFORNIA ST PASADENA CA 91109
2	GA INST OF TECH SCHOOL OF AEROSPACE ENGRG ATTN B ZIM E PRICE ATLANTA GA 30332
2	UNIV OF ILLINOIS DEPT OF MECH IND ENGRG ATTN H KRIER R BEDDINI 144 MEB 1206 N GREEN ST URBANA IL 61801-2978
1	UNIV OF MASSACHUSETTS DEPT OF MECHANICAL ENGRG ATTN K JAKUS AMHERST MA 01002-0014
1	UNIV OF MINNESOTA ATTN E FLETCHER DEPT OF MECHANICAL ENGRG MINNEAPOLIS MN 55414-3368
3	PENNSYLVANIA STATE UNIV DEPT OF MECHANICAL ENGRG ATTN V YANG K KUO C MERKLE UNIVERSITY PARK PA 16802-7501

NO. OF COPIES	ORGANIZATION
1	RENSSELAER POLYTECHNIC INST DEPT OF MATHEMATICS TROY NY 12181
1	STEVENS INST OF TECH DAVIDSON LABORATORY ATTN R MCALEVY III CASTLE POINT STATION HOBOKEN NJ 07030-5907
1	RUTGERS UNIVERSITY DEPT OF MECH & AEROSPACE ENGRG ATTN S TEMKIN UNIVERSITY HEIGHTS CAMPUS NEW BRUNSWICK NJ 08903
1	UNIV OF UTAH DEPT OF CHEMICAL ENGRG ATTN A BAER SALT LAKE CITY UT 84112-1194
1	WASHINGTON STATE UNIV DEPT OF MECHANICAL ENGRG ATTN C CROWE PULLMAN WA 99163-5201
1	STANFORD UNIVERSITY MECHANICAL ENGRNG DEPT ATTN R HANSON STANFORD CA 94305-3032
1	PURDUE UNIVERSITY SCHOOL OF AERO & ASTRO ATTN N MESSERSMITH 1282 GRISSOM HALL WEST LAFAYETTE IN 47907-1282
1	GENERAL APPLIED SCIENCES LAB ATTN J ERDOS 77 RAYNOR AVE RONKONKAMA NY 11779-6649
1	FMC CORPORATION NAVAL SYSTEMS DIVISION ATTN A GIOVANETTI 4800 E RIVER RD MINNEAPOLIS MN 55421

NO. OF COPIES	ORGANIZATION
4	MARTIN MARIETTA TACTICAL SYSTEM DEPT ATTN J MANDZY I MAGOON P JORDAN D COOK 100 PLASTICS AVE PITTSFIELD MA 01201-3698
2	HERCULES INC ALLEGHENY BALLISTICS LAB ATTN W WALKUP T FARABAUGH PO BOX 210 ROCKET CENTER WV 26726
2	OLIN ORDNANCE ATTN A GONZALEZ D WORTHINGTON PO BOX 222 ST MARKS FL 32355-0222
1	OLIN ORDNANCE ATTN H MCELROY 10101 NINTH ST N ST PETERSBURG FL 33716
2	PRINCETON COMBUSTION RSRCH LABS INC ATTN N MER N A MESSINA PRINCETON CORPORATE PLAZA 11 DEERPARK DR BLDG IV STE 119 MONMOUTH JUNCTION NJ 08852
1	SAIC ATTN M PALMER 2109 AIR PARK RD ALBUQUERQUE NM 87106
1	SOUTHWEST RSRCH INSTITUTE ATTN J RIEGEL 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
1	SVERDRUP TECHNOLOGY INC ATTN DR J DEUR 2001 AEROSPACE PKWY BROOK PARK OH 44142

NO. OF COPIES	ORGANIZATION
2	VERITAY TECHNOLOGY INC ATTN E FISHER R TALLEY 4845 MILLERSPORT HWY EAST AMHERST NY 14501-0305
1	ADROIT SYSTEMS INC ATTN J HINKEY 411 108TH AVE NE STE 1080 BELLEVUE WA 98004
1	NASA ATTN CODE 5 11 B MCBRIDE CLEVELAND OH 44135-3191
2	UNIVERSITY OF WASHINGTON AERO & ENGERTICS RSRCH PRGM ATTN A BRUCKNER BOX 352250 SEATTLE WA 98195-2250
1	THE JOHNS HOPKINS UNIV APPLIED PHYSICS LABORATORY ATTN D VAN WIE LAUREL MD 20723
	ABERDEEN PROVING GROUND
1	COMMANDER USA ATC ATTN: STECS-LI R. HENDRICKSEN

NO. OF COPIES	ORGANIZATION
1	ERNST-MACH-INSTITUT ATTN: DR. R HEISER HAUPSTRASSE 18 WEIL AM RHEIM GERMANY
1	DEFENCE RESEARCH AGENCY, MILITARY DIVISION ATTN: C. WOODLEY RARDE FORT HALSTEAD SEVENOAKS KENT, TN14 7BP ENGLAND
1	DEFENCE RESEARCH AGENCY FLIGHT DYNAMIC SECTION ATTN: CASEY PHAN WX7e BLDG S 16 FORT HALSTEAD SEVENOAKS KENT TN 7BP ENGLAND
1	SCHOOL OF MECHANICAL, MATERIALS, AND CIVIL ENGINEERING ATTN: DR. BRYAN LAWTON ROYAL MILITARY COLLEGE OF SCIENCE SCHRIVANHAM, SWINDON, WILTSHIRE SN6 8LA ENGLAND
2	INSTITUT SAINT LOUIS ATTN: DR. MARC GIRAUD DR. GUNTHER SMEETS POSTFACH 1260 7858 WEAIL AM RHEIN 1 GERMANY
1	EXPLOSIVE ORDNANCE DIVISION ATTN: A. WILDEGGER-GAISSMAIER DEFENCE SCIENCE AND TECHNOLOGY ORGANIZATION P. O. BOX 1750 SALISBURY, SOUTH AUSTRALIA, 5108
1	ARMAMENTS DIVISION ATTN: DR. J. LAVIGNE DEFENCE RESEARCH ESTABLISHMENT VALCARTIER 2459, PIE XI BVLD., NORTH P. O. BOX 8800 COURCELETTE, QUEBEC G0A 1R0 CANADA

NO. OF COPIES	ORGANIZATION
1	BALLISTIC TECHNOLOGIES ATTN: PAVEL KRYUKOV MOSCOW REGION B. O. 92 KALININGRAD, MOSCOW 141070 RUSSIA
1	TOHOKU UNIVERSITY INSTITUTE FOR FLUID SCIENCE ATTN: AKIHIRO SASOH 2-1-1 KATAHIRA, AOBA SENDAI, 980-77 JAPAN
1	HIROSHIMA UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN: XINYU CHANG 1-4-1 KAGAMIYAMA HIGASHI-HIROSHIMA, 739 JAPAN

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1236 (Kruczynski) Date of Report November 1996

2. Date Report Received ______________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______________________

CURRENT ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR
U S ARMY RESEARCH LABORATORY
ATTN AMSRL WT PA
ABERDEEN PROVING GROUND MD 21005-5066